STU SvF
SLOVAK UNIVERSITY OF TECHNOLOGY IN BRATISLAVA
FACULTY OF CIVIL ENGINEERING

Slovak Journal of Civil Engineering

Vol. 34, 2026, No. 1, 57– 71
DOI: 10.2478/sjce-2026-0006

BUILDING A GREENER FUTURE: TRANSFORMING INDUSTRIAL WASTE INTO SUSTAINABLE MATERIALS

Abhishek CHANDA [1], Sonal THAKKAR [2*]

Article history

Received 13 March 2025
Revised 6 February 2026
Accepted 17 February 2026

Abstract

The construction sector significantly contributes to global carbon emissions, largely due to the widespread use of Ordinary Portland Cement (OPC). This study investigates fly ash, ground granulated blast furnace slag (GGBFS), and calcium carbide residue (CCR) as sustainable precursors for one-part alkali-activated binders. Paste and mortar specimens were prepared using a single activator comprising 4% sodium hydroxide by precursor weight, with CCR incorporated as both an additive and partial replacement at dosages of 0-10%. The results show that a CCR content of 2.5% yields an optimal mechanical performance in GGBFS-based and fly ash–GGBFS blended systems. The effects of ambient and heat curing at 60 °C on geopolymerization and strength development were evaluated. Microstructural analyses using SEM and XRD confirmed the formation of C-S-H and C-A-S-H gels, which supports the strength trends observed. Overall, the study demonstrates that CCR can serve as an effective, low-cost auxiliary activator, which enables the development of sustainable and low-carbon construction materials while offering environmental, social, and economic benefits.

Address

[1] Civil Engineering Department, Institute of Technology, Research Scholar, Nirma University, Ahmedabad, India

[2] Civil Engineering Department , Institute of Technology, Associate Professor, Nirma University, Ahmedabad, India

[*] ***Corresponding author:*** sonal.thakkar@nirmauni.ac.in

Key words

- Sodium hydroxide,
- Calcium carbide residue,
- Fly ash,
- GGBFS,
- Compressive strength.

1 INTRODUCTION

Rapid population growth and the development of accelerated infrastructure have significantly increased the demand for construction materials, particularly concrete. Global concrete consumption is projected to reach approximately 18 billion tonnes annually by 2050, which places immense pressure on natural resources and the environment (Silva et al., 2020). As ordinary Portland cement (OPC) is the primary binding constituent of concrete, its production is associated with substantial energy consumption and greenhouse gas emissions. The cement industry alone accounts for nearly 5-7% of global energy use and contributes approximately one tonne of carbon dioxide (CO_2) for every tonne of cement produced (Ahmed et al., 2021; Turner & Collins, 2013).

In response to these environmental concerns, extensive research has focused on developing sustainable alternatives to OPC without compromising mechanical and durability performances (Kanagaraj et al., 2023; Y. Li et al., 2021). Alkali-activated materials (AAMs), commonly referred to as geopolymer concretes, have emerged as promising low-carbon binders. Introduced by (Davidovits, 2002), geopolymers are synthesized through the alkaline activation of aluminosilicate-rich materials such as fly ash, ground granulated blast furnace slag (GGBFS), metakaolin, and other industrial by-products.

Conventional geopolymer systems typically rely on two-part alkaline activators that combine hydroxides and silicates. While effective, these systems are often expensive, energy-intensive, and hazardous to handle. One-part geopolymer systems, on the other hand, employ solid or simplified activators that require only the addition of water, thereby improving practicality and safety (Neupane, 2022). Developing cost-effective, user-friendly one-part systems using industrial waste, is therefore critical for large-scale adoption.

Fly ash is a finely divided residue resulting from the combustion of coal, which is widely used as supplementary cementitious materials in concrete. Developing nations such as India and China are currently contributing approximately 45% of total coal consumption and that amount is expected to increase by 3 times by 2030 (Mishra et al., 2023). In India, the majority of power is produced by thermal power plants which use low-grade Indian coal that results in 30-45% of ash content. In the year 2022-23, the annual production of fly ash in India was 275.97 million tonnes (Naskar & Sharma, 2025). Thus, the judicious use of ash produced in large quantities is essential. GGBFS or slag is a waste generated during the manufacturing process of pig iron and steel. The molten slag is quenched using high-pressure jets to generate granulated slag, which has a glassy structure. The slag is then crushed, pulverized, and screened for use in a variety of applications, most notably in the manufacturing of OPC due to its pozzolanic properties.

Calcium carbide residue (CCR) is an industrial waste of the acetylene gas industry (Jaturapitakkul & Roongreung, 2003). Generally, 64 g of calcium carbide provides 26 g of acetylene gas and 74 g of CCR residue in terms of calcium hydroxide ($Ca(OH)_2$). Therefore, a huge amount of CCR is produced in the production of acetylene gas. CCR mainly consists of $Ca(OH)_2$, which is obtained in slurry form of a high basic nature. Locally available CCR is disposed of in landfills as shown in Figure 1. According to one of the estimates, only 55% of CCR is utilised, while the rest is disposed of as landfill (Chanda & Thakkar, 2022; Horpibulsuk et al., 2013; Julphunthong et al., 2024). The chemical reaction for the formation of CCR is as follows:

$$CaC_2 + 2H_2O \overset{yields}{\rightarrow} C_2H_2 + Ca(OH)_2 \quad (1)$$

(Hanjitsuwan et al., 2018) found that the compressive strength of fly ash with CCR in a ratio of 70:30 gave a compressive strength of 40MPa at 28 days when activated with sodium hydroxide (NaOH) and a silicate combination. (Ngernkham et al., 2020) used a combination of high calcium fly ash (80%) and CCR (20%) to develop a low-cost repair material that uses NaOH and sodium silicate as activators.

In a study done on the geopolymerization process with a one part activator using sodium carbonate as an activator along with CCR, it was observed that the best combination for strength was achieved with 8% sodium carbonate (Na_2CO_3) and 2.5% CCR, which produced the maximum compressive strengths of 21.8 MPa at 1 day and 37.7 MPa at 28 days (Gao et al., 2021). In another investigation where GGBFS was activated with CCR using Na_2CO_3, it was observed that the strength loss percentage varied from 7% to 30% when the CCR dosage was varied between 2.5% to 10% (Yang et al., 2022). In an investigation on the use of carbide slag or CCR as an alternative to hydrated lime and GGBFS, it was observed that additional hydration products were formed from the rapid hydration due to an excess of $Ca(OH)_2$ in the CCR in the GGBFS mix. However, too much CCR increased the crystalline $Ca(OH)_2$ in the matrix, which made it weaker. For hydrated lime, the ideal ratio of CCR to hydrated lime was 10% at 7 days and 5% at 28 and 56 days (W. Li & Yi, 2020).

Fig. 1 *Landfill disposal of CCR*

A study explored ways to use fly ash and CCR as binders to increase the compressive strength of mortar. The compressive strength increased from 15.6 MPa to 26.0 MPa in 90 days by increasing the fineness of the binder. Furthermore, it was observed that higher curing temperatures increased the mortar's compressive strength in its early stages; however, their effects decreased over time (Namarak et al., 2017). For improving the engineering properties of mortar, (Phetchuay et al., 2014) conducted a study to assess the possibility of employing fly ash as a precursor. CCR and sodium silicate (Na_2SiO_3) acted as a activator by which CCR helped the dissolution of silicon and aluminium from the amorphous phase of fly ash. The highest strength of the fly ash CCR-based geopolymer was obtained by substituting 15% of the fly ash with CCR. (Amnadnua et al., 2013) conducted a study to assess high-strength concrete without the use of OPC. The study examined the possibility of using ground fly ash and CCR together as a novel cementing agent to create high-strength concrete. The results showed that even without OPC, the CCR-fly ash blend showed great promise as a cementing agent; it obtained compressive strengths above 50 MPa, which qualified it for use in high-strength concrete applications.

1.1 Significance of the Research

Globally, an estimated 35-40 million tonnes of CCR are generated annually; however less than 10% is reused in engineering applications (Adamu et al., 2021; Zhu et al., 2022). Its disposal in landfills leads to soil and groundwater contamination due to its high alkalinity. Despite its potential, the use of CCR as a calcium rich precursor or activator in one-part geopolymer systems remains limited.

The novelty of this study lies in the combined utilization of CCR with fly ash and GGBFS in a one-part alkali-activated system using NaOH alone as the activator. The investigation systematically evaluates CCR as both an additive and replacement under different curing regimes, while simultaneously assessing environmental, economic, and societal sustainability. This approach offers a low-cost, scalable, and environmentally responsible alternative to conventional cementitious materials.

2 EXPERIMENTAL PROGRAM

2.1 Materials

The non-calcareous fly ash used in this investigation was obtained from a local power plant near Ahmedabad, Gujarat, India as per IS 3812 specifications (IS 3812: Part 1, 2013). The elemental composition of the fly ash included SiO_2 + Al_2O_3 + Fe_2O_3 (93%), CaO (less than 9%), MgO (1.4%), and NaO_2 (0.6%). The loss on ignition was 1.1%.

The GGBFS was procured from Jindal Steel Works, Maharashtra, India, and had a significant amount of CaO (37%) and SiO_2 (36.8%) besides the Al_2O_3 (10.1%). The GGBFS used was white in appearance with 11% retention of a 45-micron Indian standard sieve.

The CCR was procured from Gujarat Industrial Development Corporation, near Ahmedabad, Gujarat, India; it mainly consisted of CaO (70.8%), SiO2 (6.5%), Al_2O_3 (2.5%) and Fe_2O_3 (3.3%). The CCR was in a slurry form; to match the particle size of the fly ash and GGBFS, it was heated at 60°C for 24 hours, cooled at an ambient temperature, and then pulverized to bring it to powder form. The XRD studies showed that the CCR was crystalline where its highest peaks were obtained between 19º and 40º. The highest peaks recorded were of the calcium and oxygen atoms. Minor elements of aluminium, silicon, and sulphur were also seen. Figure 2 represents its physical appearance; SEM and XRD patterns of precursors were used in the investigation.

Table 1 shows the chemical composition of the different precursors used while Figure 3 represents the particle size distribution curve of the fly ash, GGBFS and CCR. The NaOH used in the investigation was in the form of flakes with a 98% degree of purity. The flakes were dissolved in tap water in the required amount depending upon the molarity (M).

2.2 Design of mix and sample preparation of pastes

This study examines the effect of CCR as a source material in one-part geopolymer systems that incorporate two industrial by-products, namely, fly ash and GGBFS, both individually and in combinations. The effect of two different curing regimes on the compressive strength was also evaluated.

Tab. 1 *Chemical composition of the source materials by the XRF analysis*

Material Properties	Color	Specific Surface Area	SiO_2	Al_2O_3	Fe_2O_3	CaO	LOI
Fly ash	Light Grey	416 m^2/kg	60.03%	22.67%	8.193%	<9%	1.10%
GGBFS	White	379 m^2/kg	36.80%	10.10%	0.60%	37%	0.60%
CCR	White	290 m^2/kg	7.27%	2.05%	0.90%	78.66%	-

The CCR was incorporated either as an additional source material or as a partial replacement of the fly ash, GGBFS, or their combined precursor. One-part activation was achieved using NaOH as the sole activator. A total of 200 g of precursor material was used in each mix, with CCR dosages of 0, 2.5, 5, 7.5, and 10% by weight of the source materials. In the replacement study, the CCR substituted fly ash, GGBFS, or their combination at the dosages of 0, 2.5, 5, 7.5, and 10% by weight. The NaOH content was fixed at 4% by weight of the precursor, and a constant water-to-binder ratio of 0.30 was maintained. When the CCR was used as a replacement, both the total precursor mass (200 g) and the water content (60 g) were kept constant to ensure consistency across all the mixes.

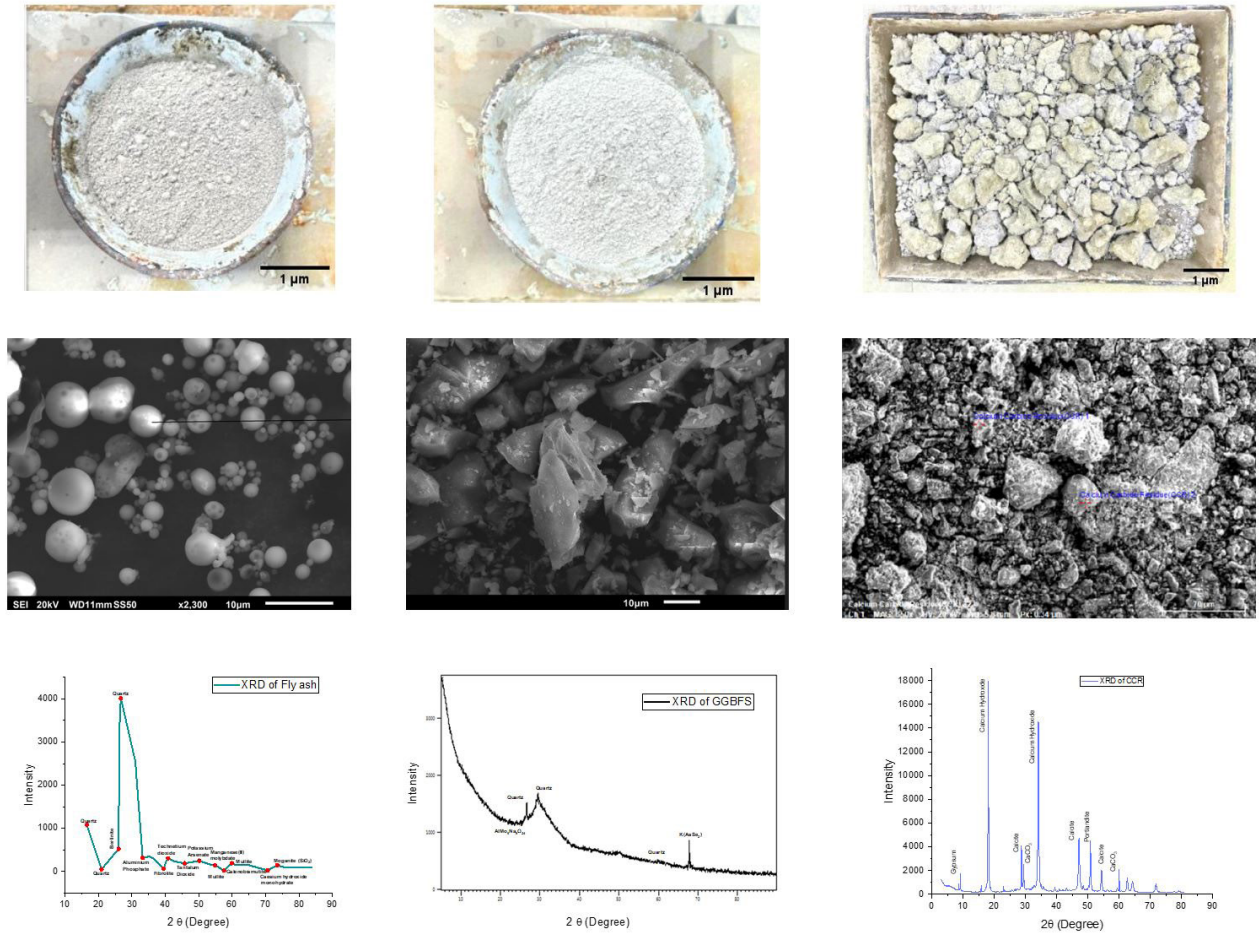

Fig. 2 *Characterization of Precursors viz. fly ash, slag and CCR showing physical appearance, SEM image and XRD plots.*

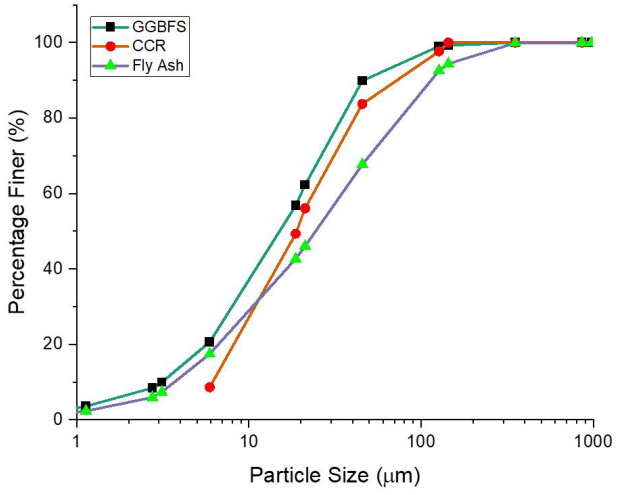

Fig. 3 *Particle size distribution of source material*

The paste specimens were prepared by initially dry-mixing the precursor materials for 3-4 minutes. The alkaline activator was then added, and the mixture was mechanically mixed until a homogeneous paste was obtained. The fresh paste was cast into cube moulds and allowed to rest for 24 hours. Subsequently, six specimens from each mix were subjected to ambient curing, while the remaining six specimens were oven-cured at 60 °C for 24 hours. After the heat curing, the oven-cured specimens were transferred to ambient conditions until the designated testing age. The ambient curing involved exposure to natural air and sunlight throughout the curing period.

For each mix, three specimens were tested under each curing regime for 7 days and another three for 28 days, which resulted in a total of 12 cubes per mix. The heat curing was employed to accelerate the geopolymerization process by subjecting the specimens to elevated temperatures during an early stage. Typically, after the initial setting, the specimens were placed in an oven maintained at 60-90 °C for 24 hours and then gradually cooled to room temperature. This curing approach promotes the development of rapid strength and is particularly advantageous for applications requiring early-age strength. Figure 4 illustrates the flow diagram of the materials used in the one-part activation process for mortar preparation. Figure 5 shows the different paste samples activated with the NaOH solution. An evaluation of the compressive strength of the paste samples was carried out on the cubes (50 mm × 50 mm × 50 mm) for both ambient and heat curing conditions for 7 and 28 days.

2.3 Design of mix and sample preparation of mortar

For the preparation of the mortar specimens, fine aggregates from three grading zones (Grades I, II, and III) were used in equal proportions with the precursor material to maintain a binder-to-fine aggregate ratio of 1:3. After achieving a homogeneous dry mix, the NaOH solution was added, and the mixture was blended in a mortar mixer at progressively increasing speeds for a total duration of 120 seconds.

Mortar cube specimens measuring 70.6 mm × 70.6 mm × 70.6 mm were cast, and the moulds were greased before casting. After casting, the moulds were placed on a mechanical vibrator to ensure proper compaction. The specimens were then kept under ambient conditions for an initial resting period of 24 hours. Following demoulding, the mortar cubes were cured under ambient conditions for 7 and 28 days.

Compressive strength tests were conducted using a compression testing machine with a loading capacity of 3000 kN; a constant loading rate of 0.3 kN/cm^2 was applied. Mixes designated as Mor1 and Mor2, which corresponded to the optimum CCR dosages, were incorporated with fly ash alone and GGBFS alone, respectively. The mixes labeled Mor3 to Mor7 represent mortar specimens containing CCR in combinations with fly ash and GGBFS.

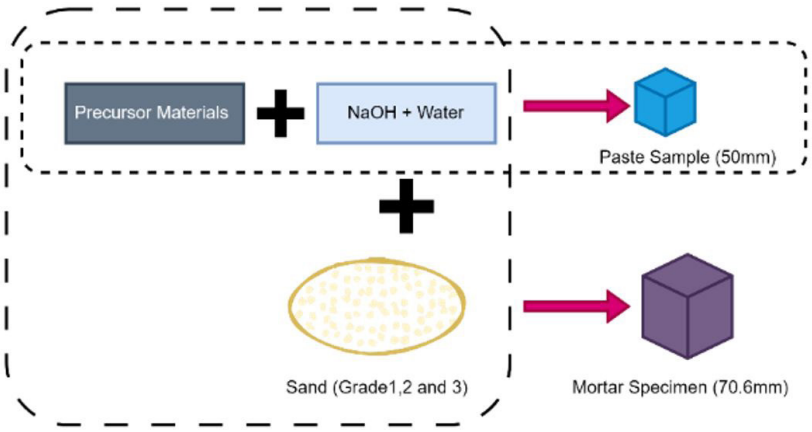

Fig. 4 *Process of one-part activation*

Fig. 5 *Paste sample under ambient curing*

3 RESULTS AND DISCUSSIONS

3.1 Setting Time

The fly ash CCR-based geopolymer paste had a prolonged setting time; it required more than 10 hours to initiate hardening. In contrast, the pastes incorporating GGBFS and CCR showed rapid setting; however, surface microcracking was observed, primarily due to shrinkage effects. When a ternary blend of fly ash, GGBFS, and CCR was activated using a NaOH solution, the setting time was significantly reduced to approximately 30 minutes, which is comparable to that of OPC. This indicates that the combined use of CCR with fly ash and GGBFS results in an optimal setting behavior when activated with NaOH.

3.2 Compressive strength of fly ash pastes with CCR

The compressive strength of the fly ash-based geopolymer pastes increased with increasing the CCR content under both ambient and oven-dry curing conditions. At 7 days, the compressive strength increased from 3.6 to 5.1 MPa under ambient curing and from 4.4 to 6.3 MPa under oven curing as the CCR content increased from 0% to 15%. Similarly, at 28 days, their strength increased from 5.9 to 7.9 MPa and from 6.0 to 9.1 MPa under ambient and oven-dry curing, respectively. The CCR contents exceeding 15% resulted in a reduction in compressive strength under both curing regimes.

The strength enhancement observed is attributed to the presence of CaO in CCR, which contributed to additional binding phases under both curing conditions. Figure 6 illustrates the development of strength at 7 and 28 days for the ambient and oven-dry curing regimes. As shown in Figure 6, the Mix 4 which contained 7.5% CCR and fly ash, achieved the highest compressive strength, primarily due to the formation of calcium-alumino-silicate-hydrate (C-A-S-H) gel (Gao et al., 2021). A reduction in strength was observed when the CCR content was increased to 20%, which was consistent with previous findings (Ngernkham et al., 2020). This loss of strength is attributed to the excessive formation of the C-S-H and C-A-S-H phases, which led to rapid chemical reactions between the free $Ca(OH)_2$ and CaO from the CCR and the reactive silica and alumina in the fly ash. Such accelerated reactions may hinder complete geopolymerization, thereby resulting in a less compact matrix and reduced strength development.

When the fly ash was partially replaced with the CCR at levels ranging from 0 to 10% and activated using NaOH, the highest compressive strength was achieved at a CCR replacement level of 7.5%. At this dosage, compressive strengths of 5.9 MPa and 6.7 MPa were obtained at 7 and 28 days, respectively, under ambient curing, while corresponding strengths of 6.4 MPa and 8.3 MPa were recorded under the oven-dry curing. Figure 7 illustrates the development of strength under both curing regimes for varying CCR replacement levels.

Geopolymerization in fly ash-based systems is inherently slow due to the low reactivity of fly ash. The incorporation of the CCR enhanced the compressive strength by supplying CaO, which promoted the formation of sodium-calcium-alumino-silicate-hydrate (Na-C-A-S-H) gel. However, at higher CCR replacement levels, the excessive liberation of $Ca(OH)_2$ likely increased the matrix porosity, which resulted in reduced compressive strength.

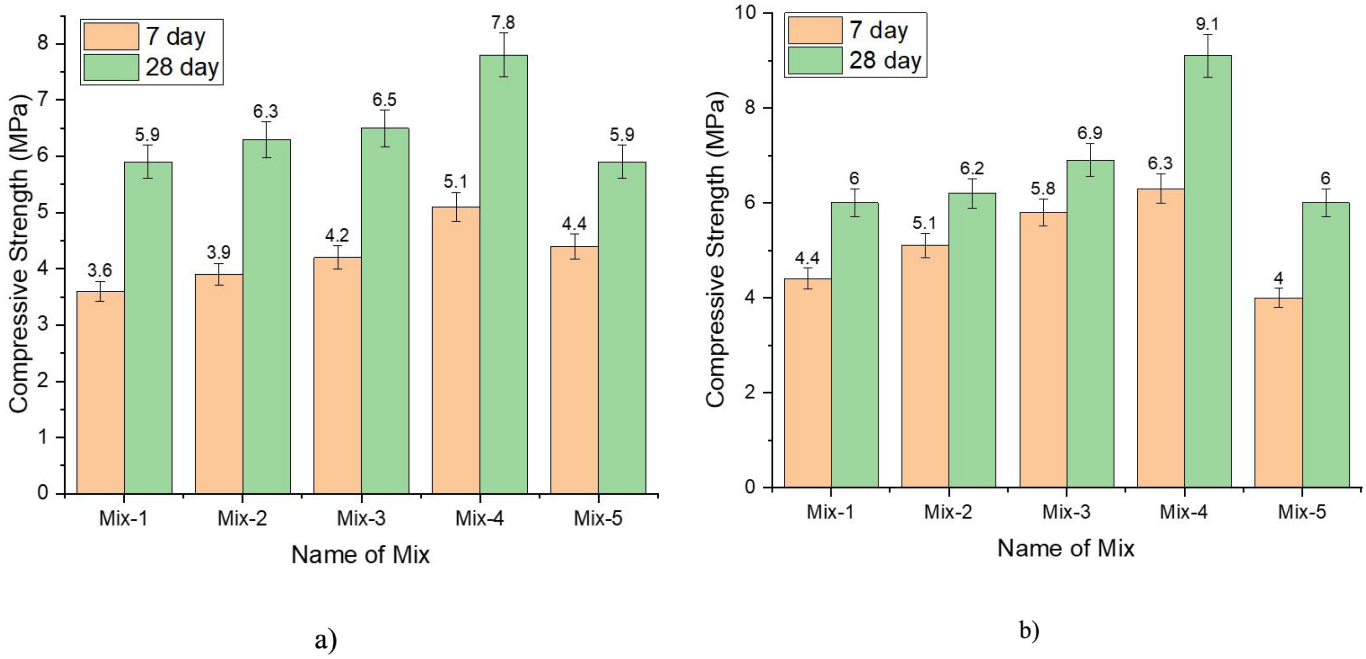

Fig. 6 Compressive strength of fly ash pastes with the addition of CCR at ambient and oven dry curing, respectively

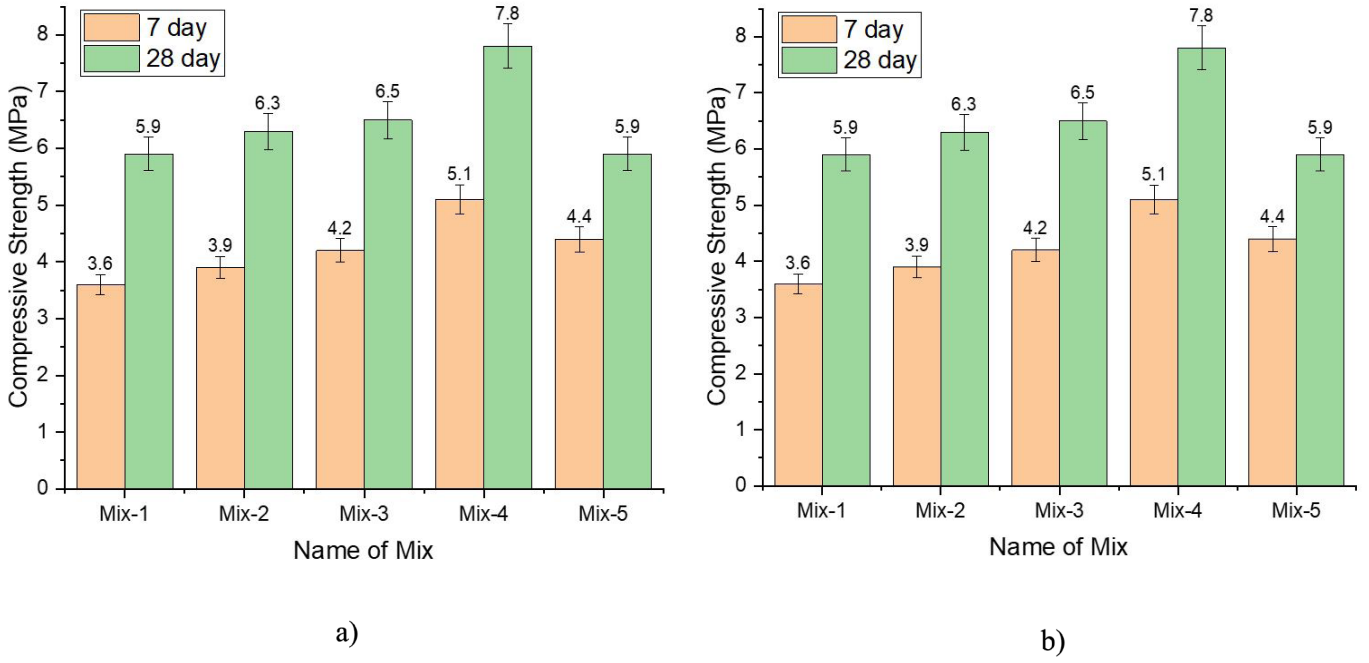

Fig. 7 Compressive strength of fly ash pastes with the addition of CCR at ambient and oven dry curing, respectively

3.3 Compressive strength of GGBFS pastes with CCR

The optimum dosage of CCR with GGBFS was 2.5%, which achieved a compressive strength of 20.2 MPa and 28 MPa at 7 days and 22.5 MPa and 32.7 MPa at 28 days, under ambient and oven curing conditions respectively as shown in Figure 8.

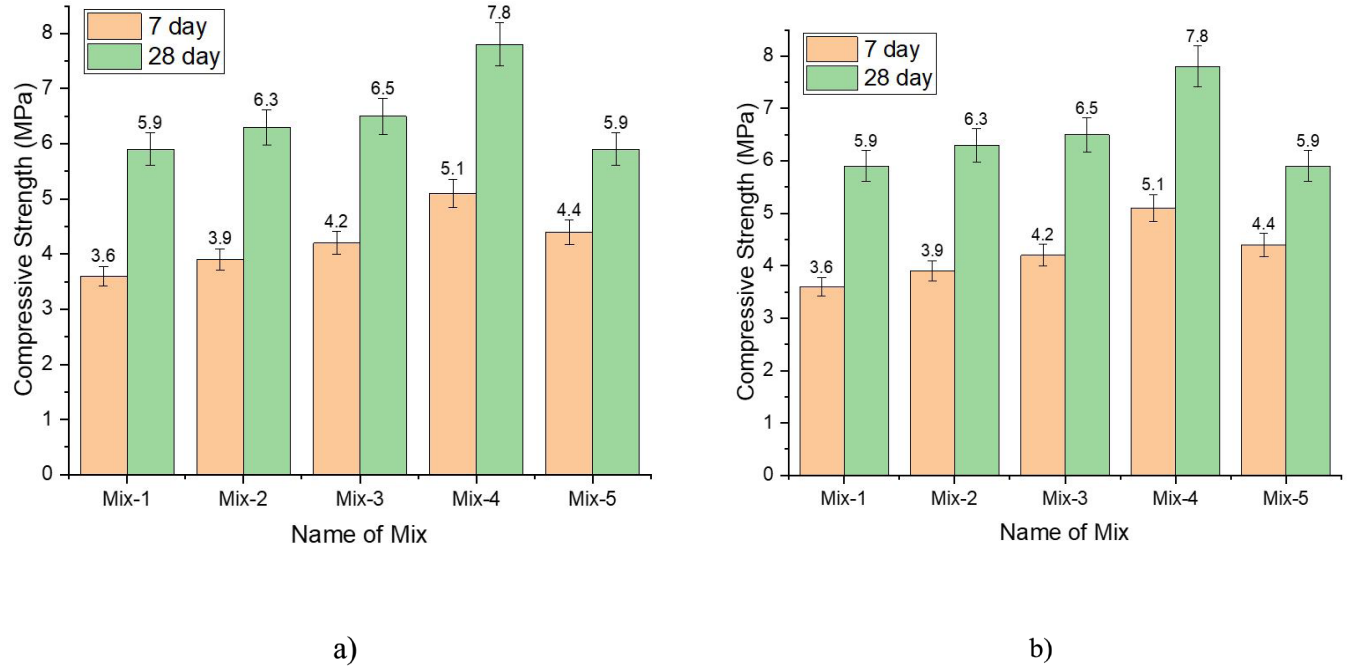

Fig. 8 Compressive strength of GGBFS pastes with CCR replacement at ambient and oven dry curing, respectively

When the CCR was used as a partial replacement for the GGBFS at levels ranging from 0 to 10% in increments of 2.5%, an optimal CCR dosage of 5% was identified. At this replacement level, compressive strengths of 27.6 MPa and 29.7 MPa at 7 days, and 31.5 MPa and 30.7 MPa at 28 days were achieved under ambient and oven-dry curing conditions, respectively, as illustrated in Figure 9.

The GGBFS-rich mixtures exhibited surface microcracking, which became more pronounced with the increasing CCR content. As both GGBFS and CCR are rich in CaO, the higher CCR dosages reduced their workability and intensified their shrinkage-related effects, thereby adversely affecting their compressive strength (Amnadnua et al., 2013).

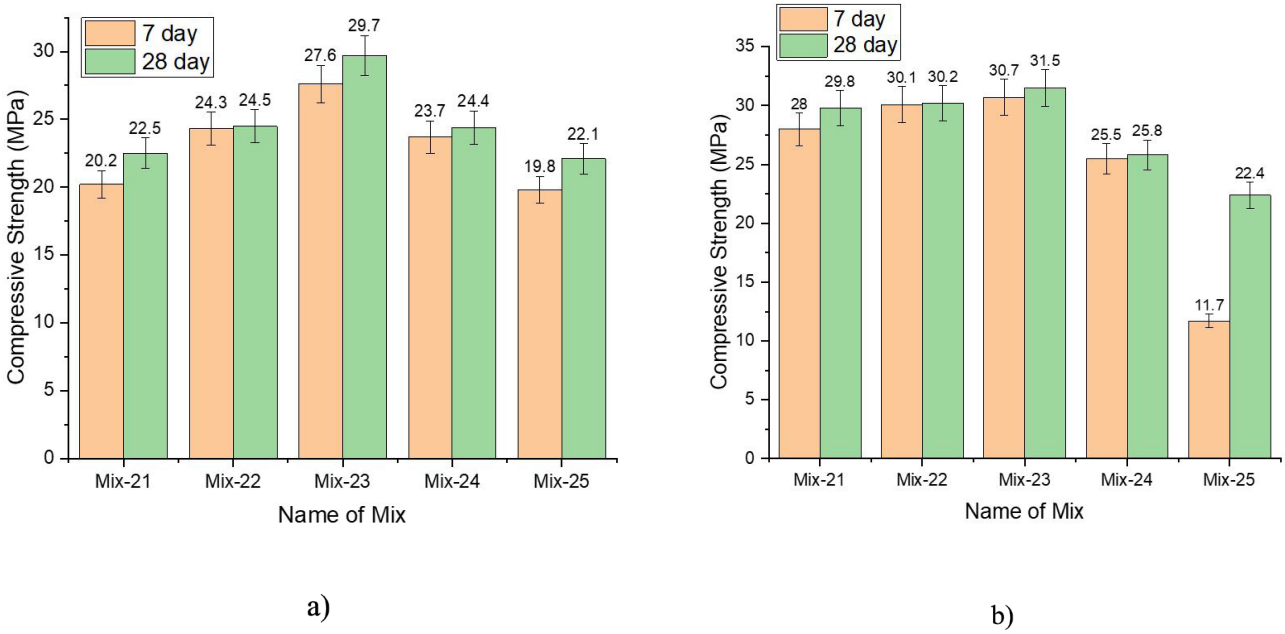

Fig. 9 *Compressive strength of GGBFS pastes with CCR replacement at ambient and oven dry curing, respectively*

3.4 Compressive strength of fly ash-GGBFS pastes with CCR

When the fly ash and GGBFS were combined in equal proportions and activated with a NaOH solution containing varying CCR dosages, improvements in workability, setting times, and compressive strength were observed. The highest compressive strength was achieved at a CCR dosage of 2.5%. Under ambient curing, strengths of 25.6 MPa and 34.1 MPa were recorded at 7 and 28 days, respectively, while corresponding values of 27.3 MPa and 32.1 MPa were obtained under oven-dry curing, as shown in Figure 10.

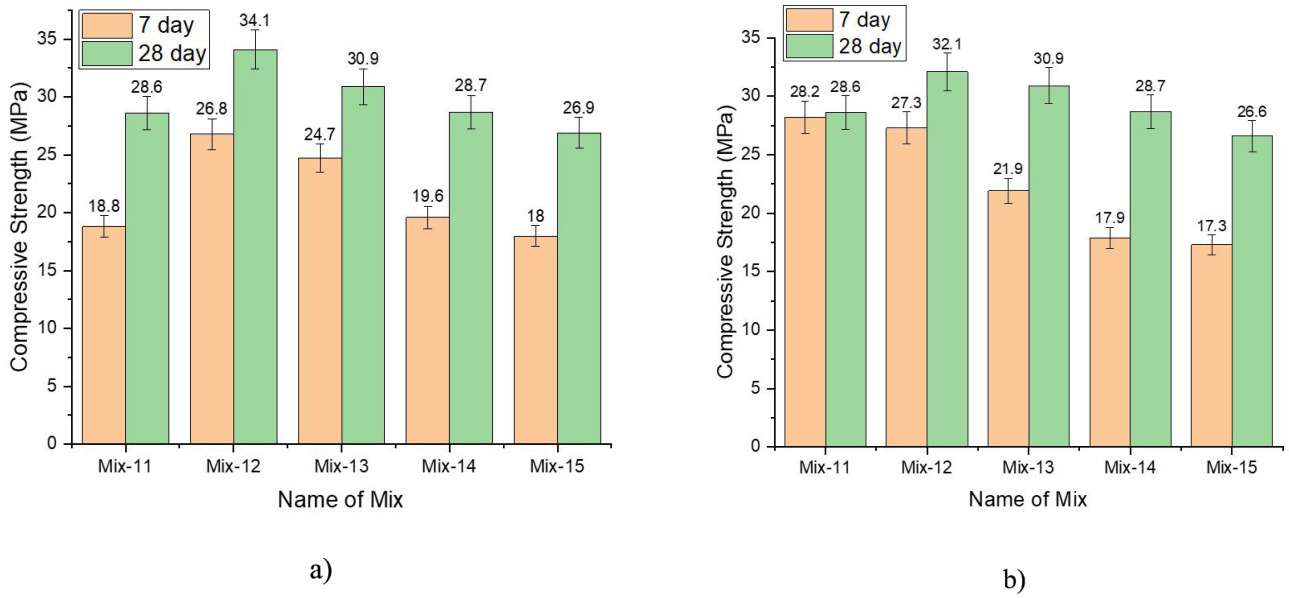

Fig. 10 *Compressive strength of fly ash-GGBFS pastes with the addition of CCR at ambient and oven dry curing, respectively*

When the CCR was used as a partial replacement for the combined fly ash-GGBFS precursor, the maximum compressive strength occurred at a CCR replacement level of 5% under both curing regimes. Strengths of 18.1 MPa and 29.8 MPa were obtained at 7 and 28 days under ambient curing, while the oven-dry curing resulted in strengths of 27.3 MPa and 31.7 MPa, respectively, as illustrated in Figure 11. The enhanced performance of the ternary system can be attributed to the complementary reactivity of fly ash and GGBFS in the presence of CCR. GGBFS reacts rapidly, while fly ash participates more gradually through its interaction with the $Ca(OH)_2$ supplied by the CCR, thus leading to the continuous formation of C-A-S-H gels. This synergistic reaction promotes a dense and stable microstructure that minimizes excessive porosity and microcracking (Du & Yang, 2021) (Makaratat et al., 2010, 2011). However, higher CCR dosages reduced workability, which necessitated additional water; this likely contributed to the observed reduction in compressive strength at elevated CCR contents (Namarak et al., 2017).

The mortar specimens were investigated using the optimal compositions identified from the paste studies for fly ash-CCR and GGBFS-CCR systems under ambient curing conditions to assess their practical applicability. As the combined fly ash-GGBFS system with varying CCR dosages exhibited superior performance at the paste level, all the corresponding mix proportions were further examined in the mortar specimens to better understand the reaction mechanisms among the fly ash, GGBFS, and CCR.

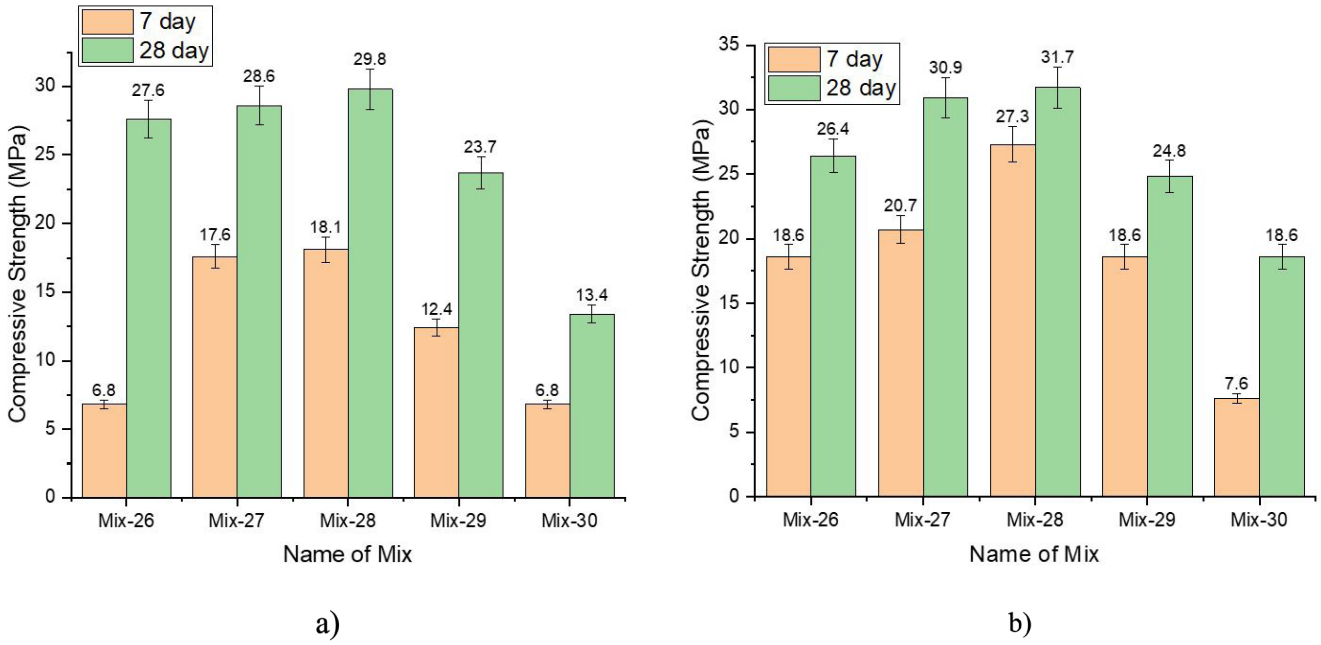

Fig. 11 *Compressive strength of fly ash-GGBFS pastes with a CCR replacement at ambient and oven dry curing, respectively*

3.5 Compressive strength of fly ash-GGBFS mortar with CCR

The mortar specimens prepared with fly ash and 7.5% CCR exhibited negligible compressive strength, which indicated insufficient geopolymerization when activated with NaOH under ambient curing conditions. In contrast, the combination of GGBFS with 2.5% CCR (Mor2) achieved compressive strengths of 6.8 MPa and 17.6 MPa at 7 and 28 days, respectively. For the ternary system, fly ash and GGBFS were used in equal proportions as the precursor material, with CCR incorporated at dosages ranging from 0% to 10% in increments of 2.5%. These mortar specimens, designated as Mor3 to Mor7, were activated using NaOH and cured under ambient conditions.

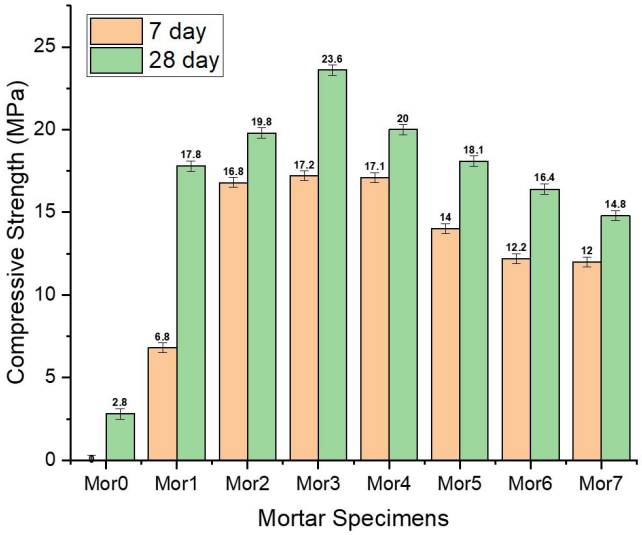

Fig. 12 *Compressive strength of fly ash-GGBFS Mortar with CCR at ambient curing*

As observed from the mortar test results, a CCR dosage of 2.5% yielded the highest compressive strength for the fly ash-GGBFS combination. Table 2 summarizes the compressive strength values of the mortar specimens after 7 and 28 days of ambient curing, along with the corresponding standard deviations for each mix. Figure 12 illustrates the development of the compressive strength of the mortar specimens. As evident from Figure 12, the fly ash-GGBFS system incorporating 2.5% CCR achieved compressive strengths of 17.9 MPa and 23.6 MPa at 7 and 28 days of ambient curing, respectively.

Tab. 2 *Compressive strength of geopolymer mortar*

Name of Mix	Compressive Strength at 7 days (MPa)	Compressive Strength at 28 days (MPa)
Mor0	0	2.8
Mor1	6.8	17.8
Mor2	16.8	19.8
Mor3	17.2	23.6
Mor4	17.1	20
Mor5	14	18.1
Mor6	12.2	16.4
Mor7	12	14.8

3.6 Social aspect on part of activation using industrial waste

The potential for improving the public health, generating economic possibilities, and enhancing environmental sustainability are the main social implications of using industrial waste in concrete. Reusing CCR lessens the environmental hazards connected to its disposal in a landfill, which can contaminate air and groundwater. This promotes a cleaner and healthier environment for nearby communities and is consistent with the ideas of the circular economy. Furthermore, encouraging the efficient use of CCR can spur changes in legislation and educational programs that increase public knowledge of sustainable waste management. Promoting community involvement in CCR repurposing enhances the socioeconomic advantages of turning industrial waste into useful resources and promotes ethical industrial operations.

3.6.1 Environmental Sustainability

The environmental sustainability of using CCR is primarily evaluated based on its impact on resource conservation, waste management, and the reduction of CO_2 emissions. The environmental footprint of CCR can be significantly minimized through its integration into industrial processes, soil stabilization, and construction materials. One of the key sustainability advantages of CCR lies in its potential to reduce CO_2 emissions. In one-part geopolymer concrete, CCR can partially replace commercial alkali activators such as sodium silicate, which results in a reduction in the energy consumption of manufacturing of approximately 30-40%.

Additionally, CCR plays a crucial role in landfill reduction and waste valorization. The reuse of CCR in concrete and soil stabilization applications can reduce landfill disposal by up to 70%, when one considers that global acetylene gas production generates an estimated 400,000–500,000 tonnes of CCR annually. Owing to its high $Ca(OH)_2$ content, CCR serves as an energy-efficient alternative to mined lime, whose production typically requires calcination temperatures of 900-1000 °C. Furthermore, CCR-based geopolymer concrete can reduce water consumption by up to 40% compared to conventional OPC-based systems. The utilization of CCR to replace up to 25% of lime in soil stabilization and approximately 20% of alkali activators in geopolymer concrete further decreases dependence on virgin raw materials (Intarabut et al., 2024; Liu et al., 2024; Mohammed et al., 2023).

3.6.2 Improved Public Health

A major public health benefit of integrating CCR is the reduction in air pollution and associated respiratory illnesses. Fine particulate matter (PM2.5) emitted from cement production has been directly linked to respiratory diseases, lung cancer, and cardiovascular disorders, while the cement industry contributes approximately 6-8% of global CO_2 emissions. Studies indicate that workers and nearby communities exposed to cement dust over extended periods are 30-50% more likely to develop chronic respiratory conditions. In contrast, substituting 10-20% of cement with CCR can reduce CO_2 emissions and particulate matter by up to 18%, thereby improving air quality and lowering the incidence of respiratory diseases (Nattapong Makaratat et al., 2018).

The use of CCR also mitigates occupational health risks in the mining and cement industries. Prolonged exposure to cement dust is associated with skin disorders, lung infections, and silicosis, which affect approximately 15-30% of exposed workers. Furthermore, around 12% of global mining fatalities due to occupational lung diseases are attributed to raw lime mining. Replacing mined lime with CCR in soil stabilization and alkali-activated materials significantly reduces workers' exposure to harmful dust, thereby resulting in safer working conditions. Beyond health benefits, the transition toward sustainable CCR utilization supports the creation of green jobs in waste processing, soil stabilization, and geopolymer production, which contributes to improved economic opportunities, reduced illness rates, and enhanced living standards in communities adopting sustainable construction practices (Endait & Sambre, 2024; Gupta, 2025).

3.6.3 Cost Effectiveness

A Cost reduction in the cement and construction sectors represents one of the principal advantages of incorporating CCR. OPC costs approximately USD 100-120 per tonne worldwide, which makes cement-intensive construction economically demanding. Studies indicate that replacing 10-20% of OPC with CCR can reduce material costs by approximately 8-15% per cubic metre of concrete. Furthermore, CCR-based alkali activation can lower activator costs in geopolymer concrete by 20–30%, thereby improving overall economic feasibility.

Beyond direct material savings, CCR promotes waste valorization and industrial synergy. Global acetylene gas production generates an estimated 400,000-500,000 tonnes of CCR annually, with landfill disposal costs ranging from USD 20 to 50 per tonne, which results in an annual financial burden of USD 10-25 million. Utilizing CCR in chemical, construction, and soil stabilization applications eliminates these disposal costs and transforms the material from a waste product into a value-generating resource. This circular economy approach not only reduces landfill pressure but also creates additional revenue streams.

CCR-based geopolymer concrete and sustainable cement alternatives are increasingly in demand as countries such as China, India, and members of the European Union adopt low-carbon construction practices. Industries leveraging CCR for green construction can therefore access expanding international markets for alkali-activated binders and sustainable building materials. Additional economic benefits arise from energy savings and improved production efficiency. Conventional cement manufacturing requires approximately 3,300-4,200 MJ of energy per tonne, which contribute significantly to operating costs. Partial replacement of cement or sodium silicate with CCR in geopolymer systems can reduce energy consumption by 15-25% per unit of material produced (Rodygin et al.,). Table 3 summarizes the carbon dioxide emissions associated with the materials consumed in $1m^3$.

Tab. 3 *CO_2 emission factors of the raw materials used in the present study*

Name of Material	Emissions ($kgCO_2$.eq/ kg)	References
Fly ash	0.01 - 0.03	(O'Brien et al., 2009; U.S. Environmental Protection Agency, 2015)
Calcium Carbide	3.6	(U.S. Environmental Protection Agency, 1975)
CCR	0.0035	(Julphunthong et al., 2024)
GGBFS	0.30	(Flower & Sanjayan, 2007)
NaOH	1.6	(Rincón et al., 2023)
Water	0.0009	(B. Li et al., 2023; Sulbarán et al., 2024)

3.7 Microstructure Analysis

3.7.1 Scanning Electron Microscope (SEM)

The FE-SEM images reveal the presence of partially unreacted fly ash particles, which explains the relatively low strength of fly ash-based systems and highlights the critical effect of curing conditions on geopolymerization, as shown in Figure 13. For samples activated with 7.5% CCR and 4% NaOH, a limited reaction of fly ash particles was observed at the periphery of the CCR grains, while several fly ash particles remained unreacted, thereby indicating incomplete geopolymerization.

Figure 13 also presents FE-SEM images of GGBFS-based pastes incorporating 2.5% CCR, which exhibit a dense and compact microstructure composed of highly reactive GGBFS and CCR particles. Angular and needle-like morphologies, which can be attributed to ettringite formation from GGBFS, are clearly visible. The presence of densely packed C-S-H gels accounts for the enhanced strength development. In addition, irregular hexagonal plate-like structures surrounded by coagulated products were observed and identified as stratlingite in the GGBFS-CCR geopolymer matrix.

The ternary fly ash-GGBFS-CCR system (50:50 fly ash-GGBFS with 2.5% CCR) shows a notably denser microstructure; this indicates synergistic interactions among the precursors when activated with NaOH. The micrographs display spherical cenospheres characteristic of fly ash, rod-like tubular ettringite structures originating from GGBFS, and angular CCR particles, which confirms an active reaction among all the constituents. Minor microcracks were also observed, which are likely due to shrinkage effects (Buchwald et al., 2009; Yang et al., 2012). These microstructural observations are consistent with the corresponding XRD results for all the paste systems.

3.7.2 X-ray Diffraction (XRD)

Figure 13 presents the XRD patterns of fly ash, GGBFS, and the combined fly ash-GGBFS systems activated with NaOH in the presence of CCR. The lower pattern corresponds to the fly ash-CCR geopolymer paste; the intermediate pattern represents the GGBFS-based system; and the upper pattern denotes the ternary fly ash-GGBFS-CCR system.

For the fly ash-based geopolymer pastes, a broad diffuse hump between 16° and 40° indicates the presence of an amorphous aluminosilicate phase, which reflects enhanced pozzolanic reactivity. The presence of the CCR is confirmed by peaks associated with $Ca(OH)_2$; this demonstrates its role as a source of alkalinity and calcium during geopolymerization. A prominent peak at approximately 26°-27° corresponds to the formation of amorphous C-A-S-H gel, thus indicating active interaction among the fly ash, CCR, and NaOH upon hydration (Wang et al., 2022).

The GGBFS-based geopolymer exhibits broad intensity peaks in the range of 21°-37°, which is characteristic of C-S-H gel formation, which is primarily responsible for the development of strength. The peaks associated with hydrotalcite are attributed to the presence of $Ca(OH)_2$ from the CCR. At higher CCR contents, the observed reduction in strength suggests phase transformations and possible volumetric instability within the GGBFS matrix, which is consistent with previous findings (W. Li & Yi, 2020).

For the fly ash-GGBFS-CCR system, the broad diffraction humps between 27° and 35° indicate the formation of a dense and continuous reaction matrix. Peaks near 27° confirm the presence of C-S-H gel, while minor SiO_2 peaks reflect the prolonged participation of fly ash in the geopolymerization process. Additional peaks at approximately 13°, 22°, 40°, and 46° correspond to ettringite, which corroborates the FE-SEM observations. The persistence of $Ca(OH)_2$ related peaks suggests that geopolymerization and hydration reactions remain ongoing, which may contribute to further strength development at extended curing ages.

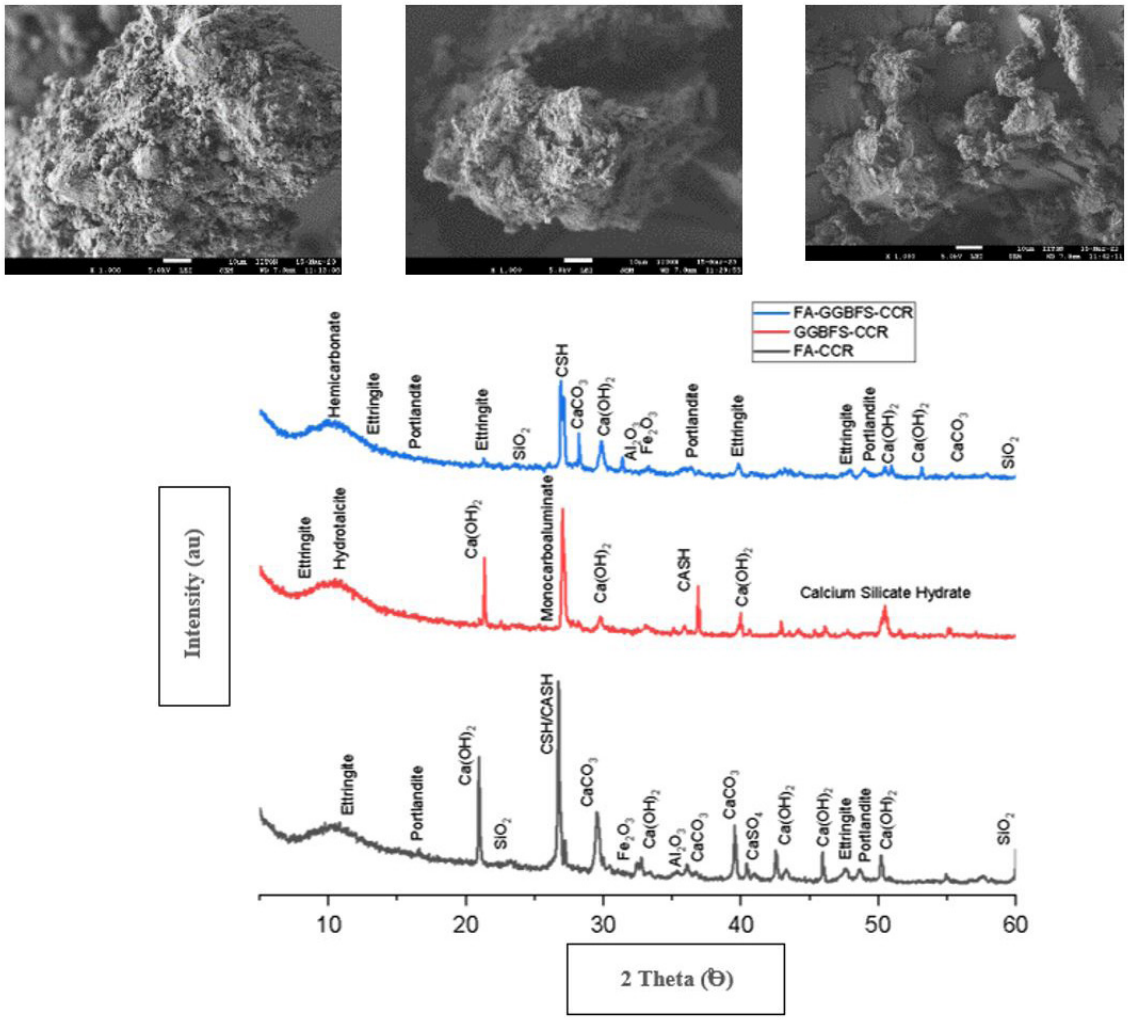

Fig. 13 *Characterization of the geopolymer paste*

The CCR, when used in combination with the fly ash and GGBFS, plays a critical role in facilitating effective one-part alkali activation using NaOH as the sole activator. This approach enables the replacement of sodium silicate, which results in a more economical and user-friendly geopolymer system. Moreover, the utilization of CCR contributes to environmental sustainability by reducing landfill disposal of industrial waste and lowering the overall carbon footprint, thereby supporting the development of greener construction materials.

4 CONCLUSIONS

The following conclusions can be drawn from the studies:

- The fly ash-CCR systems activated solely with NaOH exhibited limited geopolymerization; they achieved maximum 28-day compressive strengths of 7.8 MPa (ambient curing) and 9.1 MPa (oven curing), which indicates the need for additional reactive calcium or aluminosilicate phases.
- The GGBFS-CCR systems demonstrated effective one-part alkali activation with NaOH; they achieved optimal performance at 2.5-5% CCR, with 28-day compressive strengths reaching up to 32.7 MPa under oven curing.
- The ternary fly ash-GGBFS-CCR system showed the highest overall performance; it achieved up to 34.1 MPa at 28 days, due to the synergistic interaction between the rapidly reacting GGBFS and the slower pozzolanic contribution of the fly ash supported by calcium from the CCR.
- The microstructural (SEM and XRD) analyses confirmed that the strength development was governed by the formation of dense C-S-H and C-A-S-H gels, while the incomplete reaction of the fly ash in the binary systems explained their comparatively lower strength.
- The optimal CCR contents were identified as 2.5% for the paste specimens and 5% for the mortar specimens, beyond which excess calcium reduced their workability and adversely affected then strength, particularly in GGBFS-rich systems.

- Overall, the CCR enables an economical and environmentally sustainable one-part geopolymer system by replacing sodium silicate, reducing industrial waste disposal and carbon emissions, and delivering a performance comparable to GGBFS-only binders at a lower material cost.

This study is limited to paste and mortar-scale investigations under controlled laboratory conditions, and the performance of CCR-based one-part geopolymers was primarily evaluated in terms of compressive strength and microstructural characteristics. Future research should focus on extending the investigation to concrete-scale applications, including workability, durability, and long-term mechanical behaviour under aggressive environmental conditions. The incorporation of CCR-based one-part geopolymer systems in structural and pavement applications can further validate their suitability as low-carbon alternatives to conventional cementitious materials.

Acknowledgments

The authors are grateful to the Civil Engineering Department, Institute of Technology, Nirma University, Ahmedabad, India for their experimental set up and laboratory staff for all the guidance and cooperation.

REFERENCES

Adamu, M., Ibrahim, Y. E., Al-Atroush, M. E., & Alanazi, H. (2021). *Mechanical properties and durability performance of concrete containing calcium carbide residue and nano silica.* Materials, 14(22). https://doi.org/10.3390/ma14226960

Ahmed, H. U., Mohammed, A. A., Rafiq, S., Mohammed, A. S., Mosavi, A., Sor, N. H., & Qaidi, S. M. A. (2021). *Compressive strength of sustainable geopolymer concrete composites: A state-of-the-art review.* Sustainability (Switzerland), 13(24). https://doi.org/10.3390/su132413502

Amnadnua, K., Tangchirapat, W., & Jaturapitakkul, C. (2013). *Strength, water permeability, and heat evolution of high strength concrete made from the mixture of calcium carbide residue and fly ash.* Materials and Design, 51, 894–901. https://doi.org/10.1016/j.matdes.2013.04.099

Buchwald, A., Tatarin, R., & Stephan, D. (2009). *Reaction progress of alkaline-activated metakaolin-ground granulated blast furnace slag blends.* Journal of Materials Science, 44(20), 5609–5617. https://doi.org/10.1007/s10853-009-3790-3

Chanda, A., & Thakkar, S. (2022). *A review on the use of calcium carbide residue with various cementatious material in geopolymer concrete.* Wesleyan Journal of Research, 14(No2(II)), 89–97.

Davidovits, P. J. (2002). *30 Years of Successes and Failures in Geopolymer Applications: Market Trends and Potential Breakthroughs.* Geopolymer 2002 Conference, 1–16.

Du, C., & Yang, Q. (2021). *Experimental study of the feasibility of using calcium carbide residue as an alkaline activator for clay-plant ash geopolymer.* Construction and Building Materials, 301, 124351. https://doi.org/10.1016/j.conbuildmat.2021.124351

Endait, M., & Sambre, T. (2024). *Sustainable Usage of Calcium Carbide Residue for Soil Stabilization: A Review.* Best Practices in Geotechnical and Pavement Engineering, 215–225.

Flower, D. J. M., & Sanjayan, J. G. (2007). *Green house gas emissions due to concrete manufacture.* The International Journal of Life Cycle Assessment, 12(5), 282–288. https://doi.org/10.1065/lca2007.05.327

Gao, X., Yao, X., Yang, T., Zhou, S., Wei, H., & Zhang, Z. (2021). *Calcium carbide residue as auxiliary activator for one-part sodium carbonate-activated slag cements: compressive strength, phase assemblage and environmental benefits.* Construction and Building Materials, 308, 125015. https://doi.org/10.1016/j.conbuildmat.2021.125015

Gupta, S. (2025). *Industrial Calcium Byproduct Waste: Sustainable Construction Materials for Building Applications. ACS Sustainable Resource Management, 2(1), 212–218.* https://doi.org/10.1021/acssusresmgt.4c00435

Hanjitsuwan, S., Ngernkham, P., Yuan, L., Damrongwiriyanupap, N., & Chindaprasirt, P. (2018). *Strength development and durability of alkali-activated fly ash mortar with calcium carbide residue as additive.* Construction and Building Materials, 162, 714–723. https://doi.org/10.1016/j.conbuildmat.2017.12.034

Horpibulsuk, S., Phetchuay, C., Chinkulkijniwat, A., & Cholaphatsorn, A. (2013). *Strength development in silty clay stabilized with calcium carbide residue and fly ash. Soils and Foundations, 53(4), 477–486.* https://doi.org/10.1016/j.sandf.2013.06.001

Intarabut, D., Sukontasukkul, P., Ngernkham, P., Hanjitsuwan, S., Sata, V., Chumpol, P., Sae-Long, W., Zhang, H., & Chindaprasirt, P. (2024). *Role of Slag Replacement on Strength Enhancement of One-Part High-Calcium Fly Ash Geopolymer.* Civil Engineering Journal, 10, 252–270. https://doi.org/10.28991/CEJ-SP2024-010-013

Jaturapitakkul, C., & Roongreung, B. (2003). *Cementing Material from Calcium Carbide Residue-Rice Husk Ash. Journal of Materials in Civil Engineering,* 15(5), 470–475. https://doi.org/10.1061/(asce)0899-1561(2003)15:5(470)

Julphunthong, P., Joyklad, P., Manprom, P., Chompoorat, T., Palou, M. T., & Suriwong, T. (2024). *Evaluation of calcium carbide residue and fly ash as sustainable binders for environmentally friendly loess soil stabilization.* Scientific Reports, 14(1), 1–17. https://doi.org/10.1038/s41598-024-51326-x

Kanagaraj, B., Anand, N., Samuvel Raj, R., & Lubloy, E. (2023). *Techno-socio-economic aspects of Portland cement, Geopolymer, and Limestone Calcined Clay Cement (LC3) composite systems: A-State-of-the-Art Review.* Construction and Building Materials, 398, 132484. https://doi.org/10.1016/j.conbuildmat.2023.132484

Li, B., Wu, F., Xia, D., Li, Y., Cui, K., Wu, F., & Yu, J. (2023). *Compressive and flexural behavior of alkali-activated slag-based concrete: Effect of recycled aggregate content.* Journal of Building Engineering, 67(105993), 1–23. https://doi.org/10.1016/j.jobe.2023.105993

Li, W., & Yi, Y. (2020). *Use of carbide slag from acetylene industry for activation of ground granulated blast-furnace slag.* Construction and Building Materials, 238(117713), 1–10. https://doi.org/10.1016/j.conbuildmat.2019.117713

Li, Y., Li, J., Cui, J., Shan, Y., & Niu, Y. (2021). *Experimental study on calcium carbide residue as a combined activator for coal gangue geopolymer and feasibility for soil stabilization*. Construction and Building Materials, 312, 125465. https://doi.org/10.1016/j.conbuildmat.2021.125465

Liu, M., Liu, H., Zhu, P., Chen, C., Wang, X., & Xu, L. (2024). *Recycling potential evaluation of geopolymer concrete with different cementitious system used in freeze-thaw environment.* Case Studies in Construction Materials, 21. https://doi.org/10.1016/j.cscm.2024.e03535

Makaratat, N., Jaturapitakkul, C., & Laosamathikul, T. (2010). *Effects of Calcium Carbide Residue–Fly Ash Binder on Mechanical Properties of Concrete.* Journal of Materials in Civil Engineering, 22(11), 1164–1170. https://doi.org/10.1061/(asce)mt.1943-5533.0000127

Makaratat, N., Jaturapitakkul, C., Namarak, C., & Sata, V. (2011). *Effects of binder and CaCl2 contents on the strength of calcium carbide residue-fly ash concrete.* Cement and Concrete Composites, 33(3), 436–443. https://doi.org/10.1016/j.cemconcomp.2010.12.004

Mishra, M., Sahu, S. K., Mangaraj, P., & Beig, G. (2023). *Assessment of hazardous radionuclide emission due to fly ash from fossil fuel combustion in industrial activities in India and its impact on public.* Journal of Environmental Management, 328, 116908. https://doi.org/10.1016/j.jenvman.2022.116908

REFERENCES

Mohammed, A. A., Nahazanan, H., Nasir, N. A. M., Huseien, G. F., & Saad, A. H. (2023). *Calcium-Based Binders in Concrete or Soil Stabilization: Challenges, Problems, and Calcined Clay as Partial Replacement to Produce Low-Carbon Cement.* In Materials (Vol. 16, Number 5, pp. 1–32). MDPI. https://doi.org/10.3390/ma16052020

Namarak, C., Satching, P., Tangchirapat, W., & Jaturapitakkul, C. (2017). *Improving the compressive strength of mortar from a binder of fly ash-calcium carbide residue*. Construction and Building Materials, 147, 713–719. https://doi.org/10.1016/j.conbuildmat.2017.04.167

Naskar, J., & Sharma, A. K. (2025). *Resource and recycling: a comprehensive review of India's coal landscape, characterization, and the current to future potential of fly ash from thermal power plants.* International Journal of Coal Preparation and Utilization, 45(11), 2472–2522. https://doi.org/10.1080/19392699.2024.2428634

Nattapong Makaratat, Chaiyanunt Rattanashotinunt, & Chai Jaturapitakkul. (2018). *Low CO2 Concrete Made from Calcium Carbide Residue, Palm Oil Fuel Ash, Rice Husk-Bark Ash, and Recycled Aggregates. IEEE.*

Neupane, K. (2022). *Evaluation of environmental sustainability of one-part geopolymer binder concrete.* Cleaner Materials, 6(2), 100138. https://doi.org/10.1016/j.clema.2022.100138

O'Brien, K. R., Ménaché, J., & O'Moore, L. M. (2009). *Impact of fly ash content and fly ash transportation distance on embodied greenhouse gas emissions and water consumption in concrete.* The International Journal of Life Cycle Assessment, 14(7), 621–629. https://doi.org/10.1007/s11367-009-0105-5

Phetchuay, C., Horpibulsuk, S., Suksiripattanapong, C., Chinkulkijniwat, A., Arulrajah, A., & Disfani, M. M. (2014). *Calcium carbide residue: Alkaline activator for clay-fly ash geopolymer.* Construction and Building Materials, 69, 285–294. https://doi.org/10.1016/j.conbuildmat.2014.07.018

Ngernkham, P., Phiangphimai, C., Intarabut, D., Hanjitsuwan, S., Damrongwiriyanupap, N., Yuan, L., & Chindaprasirt, P. (2020). *Low cost and sustainable repair material made from alkali-activated high-calcium fly ash with calcium carbide residue.* Construction and Building Materials, 247. https://doi.org/10.1016/j.conbuildmat.2020.118543

Rincón, L., Ruiz, C., Contreras, R. R., & Almarza, J. (2023). *Study of the NaOH(s)-CO2(g) reaction creating value for industry: green natrite production, energy, and its potential in different sustainable scenarios.* Environmental Science: Advances, 2(7), 957–966. https://doi.org/10.1039/d2va00281g

Rodygin, K. S., Gyrdymova, Yu. V., & Ananikov, V. P. (2022). *Calcium carbide residue — a key inorganic component of the sustainable carbon cycle.* Russian Chemical Reviews, 91(7), RCR5048. https://doi.org/10.1070/rcr5048

Silva, G., Kim, S., Aguilar, R., & Nakamatsu, J. (2020). *Natural fibers as reinforcement additives for geopolymers – A review of potential eco-friendly applications to the construction industry.* In Sustainable Materials and Technologies (Vol. 23, p. e00132). Elsevier B.V. https://doi.org/10.1016/j.susmat.2019.e00132

Sulbarán, L., Lima, Y., & Mack-Vergara, Y. (2024). *Water consumption and CO 2 emissions of concrete production in Panama as a function of the mix design.* 2024 9th International Engineering, Sciences and Technology Conference (IESTEC), 422–427. https://doi.org/10.1109/IESTEC62784.2024.10820256

Turner, L. K., & Collins, F. G. (2013). *Carbon dioxide equivalent (CO□-e) emissions: A comparison between geopolymer and OPC cement concrete.* Construction and Building Materials, 43, 125–130. https://doi.org/10.1016/j.conbuildmat.2013.01.023

U.S. Environmental Protection Agency. (1975). *Calcium Carbide Manufacturing Report.*

U.S. Environmental Protection Agency. (2015). *Waste Reduction Model.*

Wang, Q., Guo, H., Yu, T., Yuan, P., Deng, L., & Zhang, B. (2022). *Utilization of Calcium Carbide Residue as Solid Alkali for Preparing Fly Ash-Based Geopolymers: Dependence of Compressive Strength and Microstructure on Calcium Carbide Residue, Water Content and Curing Temperature.* Materials, 15(973), 1–18. https://doi.org/10.3390/ma15030973

Yang, T., Gao, X., Zhang, J., Zhuang, X., Wang, H., & Zhang, Z. (2022). *Sulphate resistance of one-part geopolymer synthesized by calcium carbide residue-sodium carbonate-activation of slag.* Composites Part B: Engineering, 242(110024), 1–14. https://doi.org/10.1016/j.compositesb.2022.110024

Yang, T., Yao, X., Zhang, Z., & Wang, H. (2012). *Mechanical property and structure of alkali-activated fly ash and slag blends.* Journal of Sustainable Cement-Based Materials, 1(4), 167–178. https://doi.org/10.1080/21650373.2012.752621

Zhu, X., Niu, F., Ren, L., Jiao, C., Jiang, H., & Yao, X. (2022). *Effect of Calcium Carbide Residue on Strength Development Along with Mechanisms of Cement-Stabilized Dredged Sludge.* Materials, 15(13). https://doi.org/10.3390/ma15134453